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Clémence VANNIER [a,b], Adeline BIERRY [a], Pierre-Yves LONGARETTI [c,d], Baptiste NETTIER [e], Thomas CORDONNIER [e], Christophe CHAUVIN [e], Nathalie BERTRAND [e], Fabien QUÉTIER [f], Rémy LASSEUR [a], Sandra LAVOREL [a]

[a] Laboratoire d'Ecologie Alpine, UMR 5553 CNRS, Université **Grenoble Alpes, Université Savoie-Mont-Blanc, 38000 Grenoble, France.**
**[b] UMR 6554 LETG CNRS, Université Rennes 2, place du recteur Henri le Moal 35043 Rennes, France.**
[c] **Université Grenoble Alpes, CNRS, Inria, Grenoble INP*, LJK, 38000 Grenoble, France**
*** Institute of Engineering Univ. Grenoble Alpes, France.**
[d] Université Grenoble Alpes, CNRS-INSU, IPAG, CS 40700, 38052, Grenoble, France
[e] **Univ. Grenoble Alpes, Irstea, UR EMGR LESSEM, 2 rue de la Papeterie BP 76 38402 Saint-Martin-d'Hères cedex, France.**
[f] **Biotope, 22 Bld Foch, 34140 Mèze, France**

**Corresponding Author : Clémence Vannier**
Email : vannier.clemence@gmail.com
Phone number: +64 (0)22 6734 044

**Current address for correspondence:**
University of Canterbury,
College of Science, GeoHealth laboratory,
20 Kirkwood Ave, Upper Riccarton,
8041 Christchurch,
New Zealand

**Co-authors' emails:**
Adeline BIERRY: bierry.adeline@gmail.com
Pierre-Yves LONGARETTI: pierre-yves.longaretti@inria.fr
Baptiste NETTIER: baptiste.nettier@laposte.net
Thomas CORDONNIER: thomas.cordonnier@irstea.fr
Christophe CHAUVIN: christophe.chauvindroz@gmail.com
Nathalie BERTRAND: nathalie.bertrand@irstea.fr
Fabien QUÉTIER: fquetier@biotope.fr
Rémy LASSEUR: remy.lasseur@gmail.com
Sandra LAVOREL: sandra.lavorel@univ-grenoble-alpes.fr

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## Highlights

- A Participatory Scenario Planning process for downscaling regional normative scenarios.
- 19 institutions from 6 economic sectors involved throughout a two-year process.
- Two trend and two break-away scenarios with storylines and projected land cover.
- Three spatial models to project land use change by 2040 at 15 m resolution.
- Multi-scale participatory normative scenarios for supporting land planning.


## Abstract

Physically and socially heterogeneous mountain landscapes support high biodiversity and multiple ecosystem services. But rapid landscape transformation from fast urbanisation and agricultural intensification around cities to abandonment and depopulation in higher and more remote districts, raises urgent environmental and planning issues. For anticipating their future in a highly uncertain socio-economic context, we engaged stakeholders of a dynamic urban region of the French Alps in an exemplary interactive Participatory Scenario Planning (PSP) for co-creating salient, credible and legitimate scenarios. Stakeholders helped researchers adapt, downscale and spatialize four normative visions from the regional government, co-producing four storylines of trend versus break-away futures. Stakeholder input, combined with planning documents and analyses of recent dynamics, enabled parameterisation of high-resolution models of urban expansion, agriculture and forest dynamics. With similar storylines in spite of stakeholders insisting on different governance arrangements, both trend scenarios met current local and European planning objectives of containing urban expansion and limiting loss and fragmentation of agricultural land. Both break-away scenarios induced considerable conversion from agriculture to forest, but with highly distinctive patterns. Under a commonly investigated, deregulated liberal economic context, encroachment was random and patchy across valleys and mountains. A novel reinforced nature protection scenario affecting primarily mountain and hilly areas fostered deliberate consolidation of forested areas and connectivity. This transdisciplinary approach demonstrated the potential of combining downscaled normative scenarios with local, spatially-precise dynamics informed by stakeholders for local appropriation of top-down visions, and for supporting land planning and subsequent assessment of ecosystem service trade-offs.



## Key words

Participatory scenario planning, Scenario downscaling, Land use and land cover modelling, Landscape conversion, Mountain regions

# 1. Introduction

Societies are realising the ecological limits to socio-economic development (Griggs et al. 2013; Steffen et al. 2015). There is at the same time increased recognition of the benefits that ecosystems can provide for society (Díaz et al. 2015). Nature’s benefits and ‘Nature-Based Solutions’ are seen as supporting future socio-economic development, including in developed countries (Maes and Sanders 2017; Nesshöver et al. 2017), requiring changes in social values and governance (Colloff et al. 2017; Kabisch et al. 2016). Consistent with this movement, ecological insights, and specifically ecosystem services assessments are increasingly incorporated into land use planning (Albert et al. 2014; Cabral et al. 2016; Opdam et al. 2015 Turkelboom et al., 2017). This poses challenges to planners and decision makers for bringing ecosystem services into political agendas, building their knowledge and capacity, and producing relevant, salient and legitimate assessments of the sustainability of land plans (Albert et al. 2014). Participatory scenario planning is one of the tools to achieve this (Rounsevell et al. 2012).

Scenarios, defined as coherent and internally consistent descriptions of the future (Alcamo 2009), allow exploring a range of plausible futures without gaging their probability (Peterson et al. 2003). By exploring multiple alternative futures and exploring key uncertainties on drivers and their impacts (Kok et al. 2007; Peterson et al. 2003; Rosa et al. 2017), exploratory scenario planning promotes understanding of complex systems dynamics (Carpenter et al. 2009), and expands thinking horizons of scientists, stakeholders and decision makers. As such scenario processes foster creative solutions to environmental problems (Biggs et al. 2007; Peterson et al. 2003). In planning, normative approaches focusing on desired futures may be preferred to exploratory approaches because of their greater saliency and legitimacy (Albert et al. 2014, Castella et al. 2014). Normative, or target-seeking scenarios (Rosa et al. 2017) complement exploratory scenarios by exploring desired scenarios and comparing them to undesired ones to support the design of pathways towards preferred futures (Lavorel et al., 2019; Hanspach et al., 2014; Nieto-Romero et al., 2016; Oteros-Rozas et al., 2013; Palomo et al., 2011). Their value has recently been emphasised for empowering stakeholders in global change adaptation and for fostering institutional and social learning (Sharpe et al. 2016, van Kerkhoff et al. 2018, Lavorel et al. 2019).

Among scenario methods, participatory scenario planning (PSP) is defined as engaging stakeholders along with scientists at various stages of the scenario development process (Oteros-Rozas et al. 2015). PSP is increasingly used in environmental research including for analysing global change impacts (Harrison et al. 2015; Moss et al. 2010) or sustainable futures (Bohunovsky et al. 2011; Nieto-Romero et al. 2016). PSP has been used in ecosystem service (ES) research to integrate quantitative, and sometimes spatially-explicit ES assessments with stakeholder demand (see overviews and examples in Albert et al. 2014; Oteros-Rozas et al. 2015; Plieninger et al. 2014). Beyond usual benefits of scenario planning, PSP combines multiple sources of academic, political and civil knowledge, and fosters dialogue and social learning. In the case of environmental issues, PSP aims to foster communication, planning and cultural change from sectoral to trans-sectoral policy, planning and management.

In the last decade, land use and ecosystem service PSP has gained currency from local (Hanspach et al. 2014; Oteros-Rozas et al. 2013; Palomo et al. 2011; Plieninger et al. 2013; Schirpke et al. 2017), to national or regional (Cradock-Henry et al., 2018; Mitchell et al. 2015; Reed et al. 2013) and to continental scale (Harrison et al. 2015, Verkerk et al., 2018). However, in spite of its critical role for policy and decision-making, ecosystem service PSP has been significantly less used at sub-national regional than at landscape or municipality scales. Further, multiscale scenarios add to single-scale scenarios by combining a top-down, expert-led component to identify and downscale larger scale scenarios, and a bottom-up participatory process that provides local expertise on specific conditions, especially social, and spatial aspects (Kok et al. 2017). Developing practice in participatory multiscale scenarios (Kok et al. 2007; Lamarque et al. 2013) opens avenues for producing salient and relevant scenarios for regional land use planning.

The Grenoble region, in the French Alps, is a typical European urban region facing issues of development in a context of high environmental and amenity values and with high spatial diversity (Vannier et al. 2016). The region's agriculture depends on future policy and social orientations, also on climate and ecosystem changes and adaptations. Future local and external demands for recreation and tourism add to uncertainties to be incorporated into future scenarios (Brunner et al. 2017; Kohler et al. 2017). A broad institutional and citizen participatory urban planning process took place from 2008 to 2012 to produce a development plan (SCoT – Schéma de Cohérence Territoriale) towards 2030, aiming to reconcile a spatially balanced economic growth and environmental objectives, especially from recent French climate and biodiversity legislation and policy. In this context, the objective of this study was to showcase a highly participatory scenario downscaling approach for developing with local decision-makers high-resolution spatially-explicit land-use scenarios. The final outcome is a subsequent assessment of planning alternatives for future ecosystem services trade-offs. We aimed to develop an exemplary participatory scenario process relevant to similar urban regions in developed mountain and other regions, meeting the following criteria: (i) relevance to the specific issues of the study area, as outlined by the current land plan and as expressed by stakeholders; (ii) consistent with larger scale socio-economic scenarios through downscaling; (iii) spatially-explicit.

This paper presents four steps for co-producing downscaled normative scenarios using a combination of qualitative and quantitative methods with extensive stakeholder participation: 1) scoping of pre-existing visions and scenarios, 2) refining and spatializing scenarios with stakeholder to produce storylines, 3) projecting and 4) analysing land use change at the regional and municipality scale, and consequences for landscape patterns. We argue for the generic advantages of this participatory downscaling methodology and end with considering scenarios implications for future land planning and ecosystem services provision.

# 2. Methods

## 2.1. Study site

Grenoble is one of the most active and dynamic French metropolitan areas. With an extent of 4450 km², the Grenoble urban area hosted in 2012 around 800,000 inhabitants. Our study encompasses the area of economic influence of Grenoble, especially regarding employment. With highly diverse physical and natural characteristics, all significant landscape units in an Alpine region, plains, plateaus and mountains are represented, resulting in contrasted and heterogeneous landscapes (Figure 1). The region is structured by three mountain ranges: Vercors, Chartreuse and Belledonne, culminating at 2977m. River valleys favour urban sprawl, as well as to a lesser extent the Bièvre plain. Mountain ranges benefit from a wide range of protection measures with two natural parks and several conservation areas. Most of the 311 municipalities within 50 km of the city of Grenoble are integrated into the Grenoble SCoT[1] planning area (Schéma de Cohérence Territoriale), whose primary aim is to contain urban expansion and preserve natural assets while supporting equitable economic development at the scale of a small region. For a spatially-explicit specification of scenarios, we considered eight districts regrouping municipalities according to their biophysical features and broad land planning districts (Figure 1).

Recent land use trends are consistent with other European mountain regions. Between 1998 and 2009 urban use spread at the expense of agricultural land (29 km², + 7% over the 11 year period), either in the valleys near Grenoble or in agricultural plains (Vannier et al. 2016). This expansion was nearly exclusively a densification of urban patches or adjacent to existing urban areas, complying with current urban planning. Agricultural land-use remained stable, mostly because it is largely determined by the physical geography of the study site with permanent grasslands dominant above 800-1000 m altitude, while broad acre crops are preferentially located in the valley bottoms and plains; landscapes on plateaus and hilly areas comprise mosaics of grassland and spring crop successions (Lasseur et al., 2018). Other forest and semi-natural areas also remained stable.

1 The SCoT, Territorial Coherence Scheme is a French planning document that determines, for groups of municipalities, common objectives for urban planning, housing, transport, and business and retail areas. http://www.region-grenoble.org/index.php

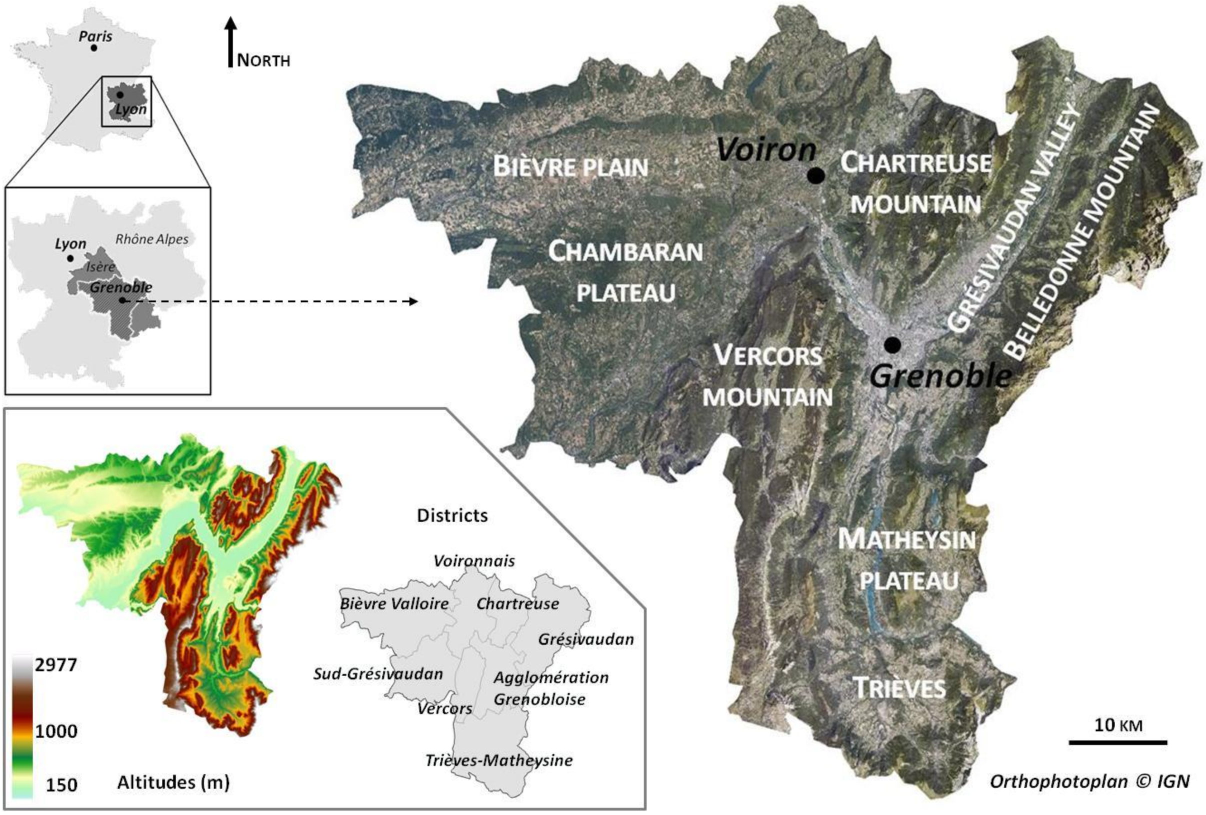


Figure 1 – Grenoble urban area: location map, districts and physical geography.

## 2.2. Participatory scenario process

In order to produce quantitative and spatially-explicit scenarios fitted to regional challenges and incorporating social, economic and governance dynamics, we developed a transdisciplinary process involving an interdisciplinary team of eight researchers along with nineteen stakeholders from the main decision and land management sectors over two years (2014-15). Researchers in biodiversity, urban planning, agronomy and forestry were involved through individual consultations and workshops. The nineteen stakeholders were involved in land management of the Grenoble area within the local government, management organisations or NGOs and represented, albeit not exhaustively, the predominant land planning, agriculture, forest, tourism, nature conservation and water management sectors (Supplementary table 1). They were part of the advisory committee established at the beginning of the research process (spring 2013) and selected among collaboration networks of researchers and through snow balling based especially on recommendations from the land planning agency and the local government (Bierry & Lavorel 2016). We note that the private and industrial sectors were not represented due to unsuccessful contacts during project initiation, and likely to their self-perceived less direct role in land management and planning.

Through three steps combining qualitative and quantitative methods (Figure 2), this process aimed to describe alternative visions by 2040 and to translate their socio-economic and governance characteristics into land use projections. Although the development plan targeted 2030, the 2040 horizon was chosen first for consistency with the strategic horizon at the larger regional (NUTS2, Rhône-Alpes) scale and second to consider more pronounced climate change impacts.

As a first step (January 2014) researchers scoped pre-existing local, national and international land-use and/or biodiversity visions and scenarios (Supplementary table 2) and their strengths and weaknesses regarding the project's objectives. The Montagne 2040 visions (Centre Economique, Social et Environnemental Régional Rhône-Alpes, 2013) were selected as most relevant and legitimate, especially given their focus on mountain challenges, which were not considered in larger-scale scenarios, and their familiarity to many stakeholders. These visions were the outcome of a complex two-year expert process led by the Rhône-Alpes administration region interrogating its development pathways given climate change, regional natural and human capital and the vulnerability of mountain economies. We analysed their context scenarios and four final storylines, and identified key driving variables such as the availability and access to natural resources. Through this process we translated the storylines as visions for the Grenoble region considering its biophysical and socio-economic specificities. These four scenarios documented main socio-economic orientations and their local translation in terms of governance, socio-economic dynamics and key activities (agriculture, forestry, water, recreation and tourism, nature conservation and land planning), land use and expected impacts on natural resources, and were summarised as a poster.

The second step aimed to produce refined qualitative, locally-specific and spatially explicit translations of the four scenarios by incorporating actors' knowledge of local issues and of social and ecological dynamics. We first aimed to critique the realism of the Montagne 2040 visions, originally designed for thought-provoking contrasts and not aimed for impact projections, and their local applicability. Second we aimed to adapt their region-wide socio-economic settings and institutions to the local context. Third we aimed to downscale the visions for the eight districts and for different socio-economic activities using qualitative, semi-quantitative and spatial information.

A one-day workshop (March 2014) attended by the nineteen stakeholders was facilitated by four researchers and a professional facilitator. Stakeholders were responsible for managing discussions within each session and for presenting collective conclusions. After an introductory presentation of objectives and of the Montagne 2040 approach, already familiar to many participants, participants were allocated to four groups, each with representation of socio-economic sectors. A researcher presented one scenario per group and coordinated a discussion on its local relevance, its main directions and limits. This discussion was supported by the poster from step 1. During the first session groups were tasked with describing ecosystem services demand for their scenario. The second session brainstormed the associated governance. Following these two sessions, each group presented in plenary their respective scenario and discussion outcomes so as to familiarise all participants with all four scenarios and their local adaptation. During the third session stakeholders were allocated to four geographic groups (each comprising two similar, adjacent districts) and successively analysed the four scenarios to specify land use and management (from the basis of the Land Use and Land Cover -LULC- map described in section 2.3.1. and Supplementary table 3), and their allocation across the eight districts using drawings and/or notes on maps. After a presentation of each group's results a final plenary discussion addressed the relevance of the resulting scenarios. This resulted in a final collective choice of directions for the project's scenarios. The transcription and the analysis of the workshop's results produced four locally-adapted and downscaled scenarios including a description of the socio-economic context, a qualitative specification of land use and management, along with semi-quantitative and spatially-explicit information.

The third step aimed to quantify the scenarios in a spatially-explicit fashion. We combined the workshop storylines and maps with a detailed analysis of planning and policy documents and of public and research reports (Supplementary table 2). The SCoT, which quantifies and specifies location of planning objectives, was the main document used as a starting point to translate scenarios into quantity and location, complemented by the management plans of the Vercors and Chartreuse regional parks. Their specifications were applied directly for the Business as usual scenario and were adjusted for the other three scenarios according to stakeholder input during the workshop. To quantify these adjustments which were often at best semi-quantitative, researchers combined workshop and SCoT data with an analysis of land-use trends since 1998, expected climate impacts (following Intergovernmental Panel on Climate Change scenario RCP 8.5), local interdisciplinary scientific expertise (ecology, agronomy, forestry, economics) and ad hoc in depth interviews with key stakeholders (e.g. land planners, regional government) to determine quantitative land allocation rules. Detailed storylines describing the socio-economic and governance context, its translation into economic activities and land-use projections were the output.

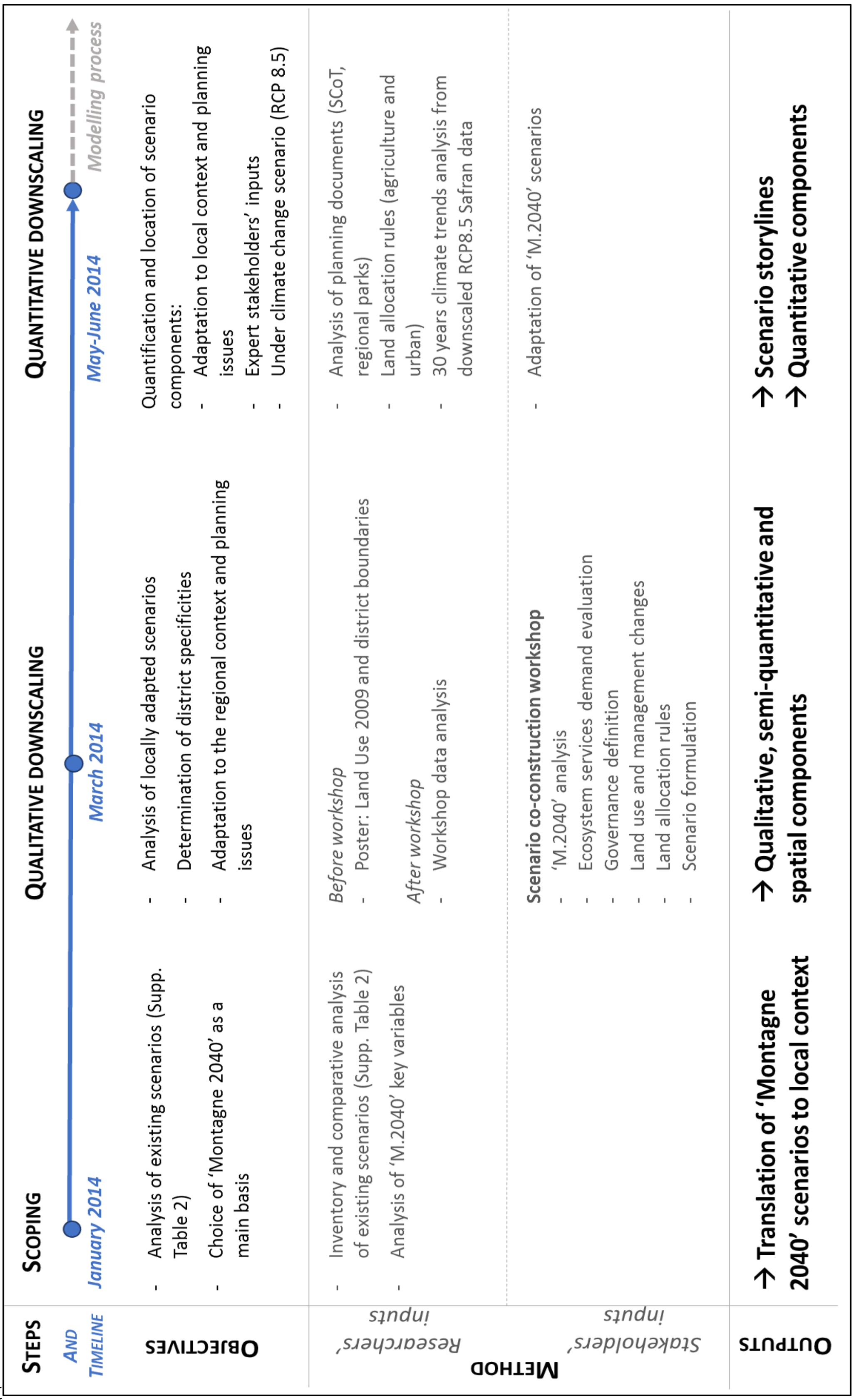


Figure 2 - Three steps for the participatory production of four locally relevant, spatially-explicit scenarios.

## 2.3. Scenario modelling

### 2.3.1. Analysis of current and past landscape dynamics

To model future land use under the four scenarios we analysed main changes in terms of amounts and spatial allocation over the 1998-2009 period. A detailed description of the data sets and analyses are provided by Vannier et al. (2016). Briefly, maps at a 1/15000 scale for 23 Land Use and Land Cover (LULC) types nested at three levels were produced for 1998, 2003 and 2009 using a multi-source approach (Supplementary table 3). These were refined for agricultural land by characterising 5-year crop type / grassland successions at parcel scale (Lasseur et al., 2018). The resulting maps, with 41 LULC classes at two levels (http://www.projet-esnet.org/en/cartes/), were analysed with a particular emphasis on urban spread dynamics, agricultural geographical patterns and land abandonment / forest regrowth.

### 2.3.2. Land use modelling

Our modelling framework operated at two spatial scales, the entire site and its eight districts (Figure 1). Simulations were run at a 5-year time step for a total of 30 years. We incorporated governance levels from the EU (e.g. the Common Agricultural Policy determining viability of mountain agriculture), to national (e.g. nature protection legislation determining zoning of protected areas), and regional or local (e.g. land planning constraining urban development). Land-use projections were modelled at the finest available scale, e.g. the parcel for agriculture, and forest or urban patches. As the analysis of recent landscape changes revealed three major types of landscape dynamics for urban, agricultural, and forested and semi-natural areas respectively, we developed three distinct models for urban spread, agricultural land and forest expansion. To achieve this, numerous types of spatial, statistical, existing data were used (Supplementary table 4) for model parametrisation (Supplementary table 5).

#### *Urban spread*

Urban spread is the most rapid process in the study area. Over periods of five years numerous but rather small patches are converted. The overall transfer from (mostly) agricultural land to urban areas is rather small, but this large number of new patches requires careful modelling in order to obtain realistic results. Two different types of processes were distinguished: the creation of new residential areas, and the creation of new industrial and commercial areas.

We used the spatially-explicit statistical modelling platform Dinamica EGO to construct our urban spread model (Soares-Filho *et al.* 2013). Transition probabilities were obtained from historical data through the statistical correlations of past changes (from Vannier et al. 2016) with spatially-explicit predictors. From an initial list of 18 such parameters, including geographical (e.g., slope) and socio-economic data (e.g., cost of real estate, employment rate at the municipality level), we retained four geographical parameters sufficient to capture most of the historical urbanization trends: altitude, slope, distance to existing urban areas, distance to roads. The statistical relevance of potential predictors was assessed through Cramer tests; their statistical independence through Cramer tests, correlation and principal component analysis. Finally, the overall quantity and location of LULC transitions were specified for the whole study area per time step, using calibration from historical data and trends specified by stakeholders and land planning documents.

### *Agricultural land*

Types of dynamics were established regarding the scenarios and quantification of dynamics was estimated regarding the past dynamics on each district. Changes in the area of agricultural land result from two distinct mechanisms. First boundary changes reflect the loss of agricultural land due to urban extension, or agricultural abandonment leading to forest regrowth. The former was simulated through the urban spread model. The latter varied across scenarios in terms of amounts and location. The historical analyses of limited change revealed a preferential abandonment of small parcels adjacent to forest and sloping and depending on altitude (Vannier et al., 2016), whereas in scenarios of massive abandonment we targeted either specific crop succession types or areas adjacent to forests of green corridors. Abandoned parcels were allocated to the “transition” land-cover type (Supplementary table 3).

Second changes in agricultural practices leading to changes in crop succession within the agricultural area were addressed with a spatial GIS model. The agricultural practices were drawn from a database of crop successions and an analysis of agricultural statistics respectively (Supplementary table 3 and 4). Scenario defined which crop successions were targeted for change, the amount of change per succession type, per district, and spatial allocation rules. For instance in the Business as usual scenario, in the Vercors district 3% of current grassland-dominated successions will incorporate a crop by 2040. Fields were targeted for change in agricultural succession depending on spatial allocation rules (proximity, distance, random effects etc.) drawn from the storylines and additional documents. Type of changes in agricultural succession were also influenced by projections of climate impacts (Ruget et al. 2013).

### *Agricultural abandonment and forest regrowth*

The model of woody encroachment and forest regrowth starts from the projections of abandoned parcels by the agricultural land model (allocated to “transition” class, Supplementary table 3 and 5). Transition to forest regrowth depends on altitude (<800 m, 800-1200 m, 1200-1500 m, >1500 m), district, nearby forest type (broadleaf, conifer, mixed forest or shrubby heathland) and time since abandonment (10-20 year-old forest, 25-30 year-old forest, 20-30 year-old woody heathland at higher altitude). The analysis of dynamics between 1998 and 2009, additional data concerning forest regrowth from 1993-1997 and farmer interviews in 2012-2014 (Supplementary table 4) allowed us to identify areas prone to woody encroachment and the temporal dynamics of forest recolonization. The type of recolonizing forest was determined from analyses of BD Topo data and of sylvo-ecoregions (Supplementary table 4). Climate change impacts were considered to already be current, whereas more drastic impacts on forest dynamics and management would not be expected until the second half of the 21th century (e.g. Seidl et al. 2011).

The agricultural and forest models were implemented using ArcGis model builder (version 10.2, ESRI Inc.).

## 2.4. Analysis of model outputs - indicators

The 2009 LULC map and its projections for 2040 were analysed in three steps. First, site-level percentages of LULC changes documenting overall dynamics of the six main classes under the scenarios. Second, municipality-level indicators summarizing relevant information for managers and decision-makers were computed. We aggregated the six main land cover classes (Supplementary table 3) to municipality and district scale for 2009 and 2040 projections and analysed their changes graphically. Third, landscape metrics were computed at the finest available map resolution documenting changes in overall spatial structure with relevance to spatially sensitive ecosystem services (Verhagen et al. 2016). We quantified landscape heterogeneity, texture, and graininess based on area, patch number (NP), mean patch size (MPS) at LULC class level; and Shannon Diversity Index (SHDI) at landscape level (Cushman et al., 2008), using Fragstats® (McGarigal et al., 2012) for the 1998-2009 (observed) and 2009-2040 (projected) periods. This landscape metrics analysis focused on the three classes undergoing most of the changes: urban, agricultural and forested areas.

# 3. Results

## 3.1. Storylines and scenario parameterisation

Four descriptive and quantitative plausible scenarios were produced, with two scenarios based on current trends and two break-away scenarios.

**Business as usual (BAU):** A local implementation of the Montagne 2040 Business as usual scenario. Based on currently existing policy and planning documents (the SCoT and regional natural park (PNR) management plans), development in this scenario is based on current regional planning and management policies. Learnings from an analysis of past dynamics are taken into account so as to maintain coherence with current trends and take into account the coordinated policy objectives of the Grenoble urban region.

**Local development:** A variant of the Business as usual scenario not considered in Montagne 2040, and not captured by its local green development vision. While like Business as usual this scenario is based on the continuation of current dynamics, the objectives of decentralised development at the regional level such as prescribed in the SCoT are not adopted. Instead, new governance arrangements with greater local control on land allocation and strengthened authority for protected areas favour focused development around selected urban centres, reinforcing their attractiveness and densifying contiguous urban expansion. In line with current policies for sustainable development and the preservation of natural areas, the emphasis is placed on local regional development via economic activity and tourism, favouring local marketing (timber, agriculture) and reinforcing regional natural parks.

**Rewilding:** A local implementation of the Montagne 2040 corresponding vision. This scenario replaces current policies with a strong nature conservation orientation, placing natural areas and in particular mountain areas in strict reserves. Consequently population and economic activities decrease drastically in these areas and are transferred to lowlands. The handicaps linked to the lack of use of these areas, and the overall reduced economic attractiveness of the region exacerbate their gradual abandonment and promote forest encroachment, while increased urbanisation and the development of currently existing economic activities are concentrated in valleys.

**Liberal:** An adapted implementation of the Montagne 2040 ultra-liberal vision which focused strongly on tourism. This scenario breaks away from current policy with a marked liberalisation of public policies, development driven by private investment, and thus major social and economic divides. The urban / rural divide is reinforced, accentuating disparities in access to resources, housing and services, as well as inequities regarding management of natural hazards. Market liberalisation and the absence of land-use regulation via public policies is detrimental to local agriculture: agricultural landscapes and practices undergo major modifications, and their area is reduced by urban expansion. Mountain areas are also affected, with development tied to attractiveness for tourism activities.

## 3.2. Overall land-use / land-cover changes

LULC maps for each scenario are presented in supplementary figure 1. Given minimal overall change under the BAU and Local development scenarios (Figure 3a), corresponding maps were quite similar to 2009. Urban spread (> +10%) around current urban areas was the major change under the BAU and Local scenarios, primarily at the expense of agricultural land (Figure 3a). In contrast, the two break-away (Rewilding and Liberal) scenarios showed large overall change, with contrasting spatial patterns (Figure 3a, b). They resulted in considerable forest expansion (+20 % and +30% respectively) at the expense of agricultural land (- 35% and -52% respectively). Under Rewilding forest expanded along already existing corridors, thus reinforcing initial spatial patterns. In the Liberal scenario land abandonment was randomly distributed in less productive areas. Given considerable encroachment, forests then become spatially continuous in less productive areas. For all four scenarios 90% of the changes concentrated below 1000m altitude (Figure 3b). Changes thus affected most strongly the Bièvre plain and the Gresivaudan valley – especially under trend scenarios, as well as hilly areas around Voironnais, and the Chambarans and Matheysine plateaus under the break-away scenarios. Conversely lower areas in Trièves appeared stable under all scenarios. The Rewilding scenario specifically affected mountain areas (20% of the total changes).

A detailed examination of the most dynamic areas (Bièvre, Grésivaudan and Vercors, Figure 3c) highlights minor changes between 2009 and both trend scenarios. Strong urban spread concentrated in the plains and valley bottoms with relatively less impacts in Vercors. The increased density of green corridors in plains constitutes the major landscape change by 2040 in the Local scenario along the edge of the Bièvre intensive agricultural area, and along the bottom of the Grésivaudan valley. This scenario pushes alignment with current French national ecological connectivity strategy to enhance and restore green spaces, connectivity between habitats, biological corridors and biodiversity reservoirs. Despite this expansion of green corridors, and due to the limited spatial extent of such linear features, the two trend scenarios did not significantly alter landscape structure at regional scale, in contrast to the break-away scenarios. Rewilding produced almost total forest colonisation of mountains, while in lowland plains and valleys forest corridors interconnected over time. In the Liberal scenario, the Vercors range remained accessible, and thus relatively attractive for economic activities, which limited landscape changes. In contrast, in the plains and valleys such as Bièvre and Grésivaudan small isolated plots outside large homogenous areas suitable for cereal crops were abandoned and encroached by forest.

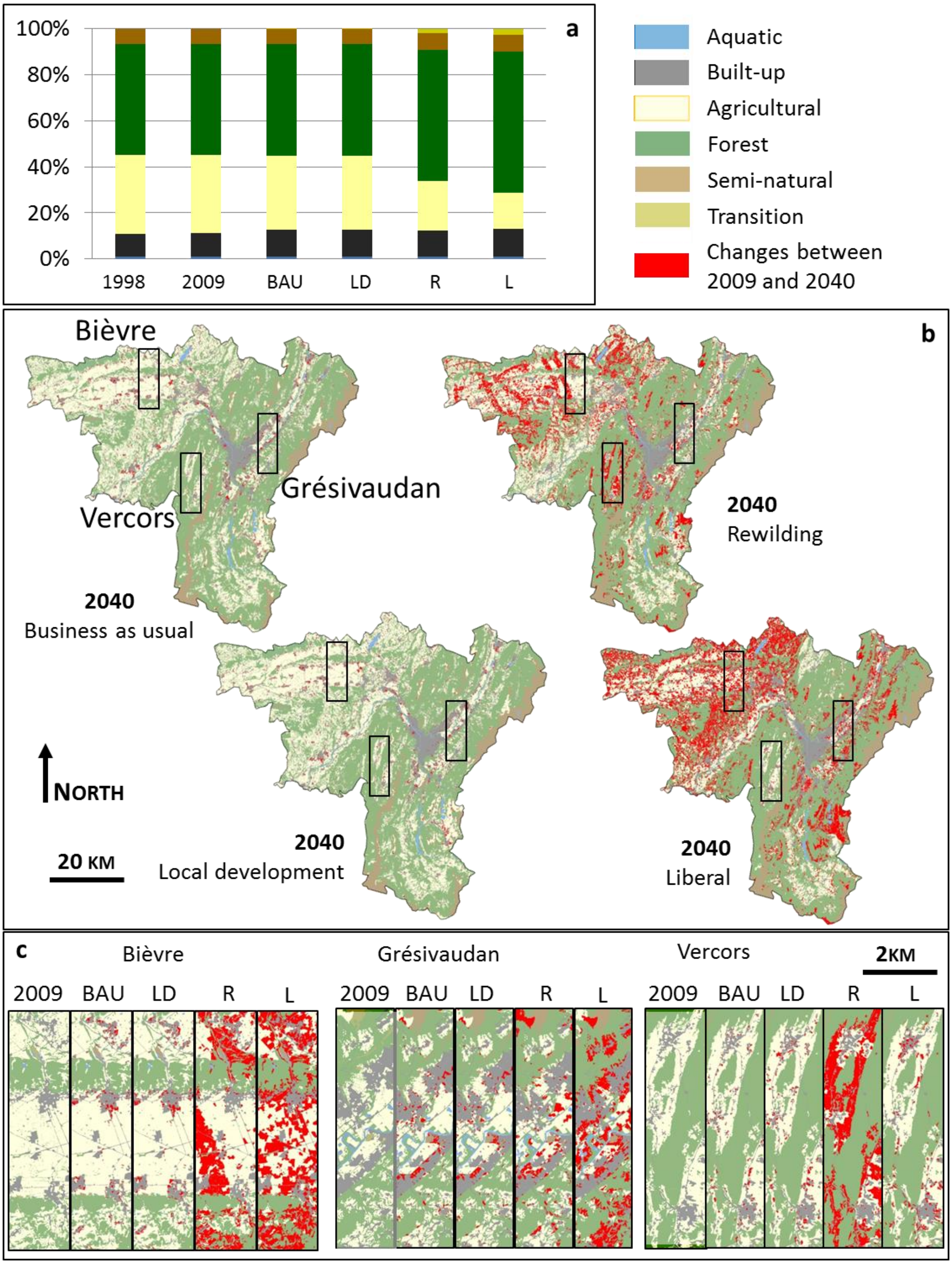


Figure 3 – Projections of the four scenarios by 2040. (a) proportions of land-use types in 1998, 2009 and for the four scenarios; (b) results of the four scenarios in 2040 over the entire study area and location of three zoomed areas; (c) zoomed details for the Bièvre, Grésivaudan and Vercors districts, for 2009 and the four scenarios. Changes between 2009 and 2040

projection are highlighted in red (b,c). BAU= Business as usual, LD= Local Development, R= Rewilding, L= Liberal.

## 3.3. Changes at municipality and sub-regional scale

Results for the municipality-level indicators showed that, initial LULC patterns in 2009 were shaped by the two largest urban centres (Grenoble and Voiron) and the surrounding urban development. Plains harboured predominantly rural municipalities, while forest-dominated municipalities were prevalent in mountains and plateaus (Supplementary figure 2). Under trend scenarios, in periurban municipalities and districts (Grenoble city, Sud Grenoblois, Grésivaudan) urbanisation tracked the 1998-2009 trend, while other districts retained their landscape identity with limited urbanisation except in Voironnais (Figure 4, Supplementary figure 2). Plains and plateaus with initial prevalence of agriculture (45-70% of their total area; Sud Grésivaudan, Voironnais, Bièvre Valloire, Matheysine) were the most sensitive areas to agricultural abandonment and forest recolonization under Rewilding, and even more under the Liberal scenario (with a doubling in forest and semi-natural areas). Scenarios thus showed them to be vulnerable rural areas. In contrast, while forest expansion up to 80-90% of their total area dominated mountain municipalities and districts under Rewilding (Chartreuse, Vercors, Trièves), under the Liberal scenario municipalities in the Vercors and Chartreuse ranges within commuting distance to Grenoble and Voiron retained their rural character with 20-30% agricultural land.

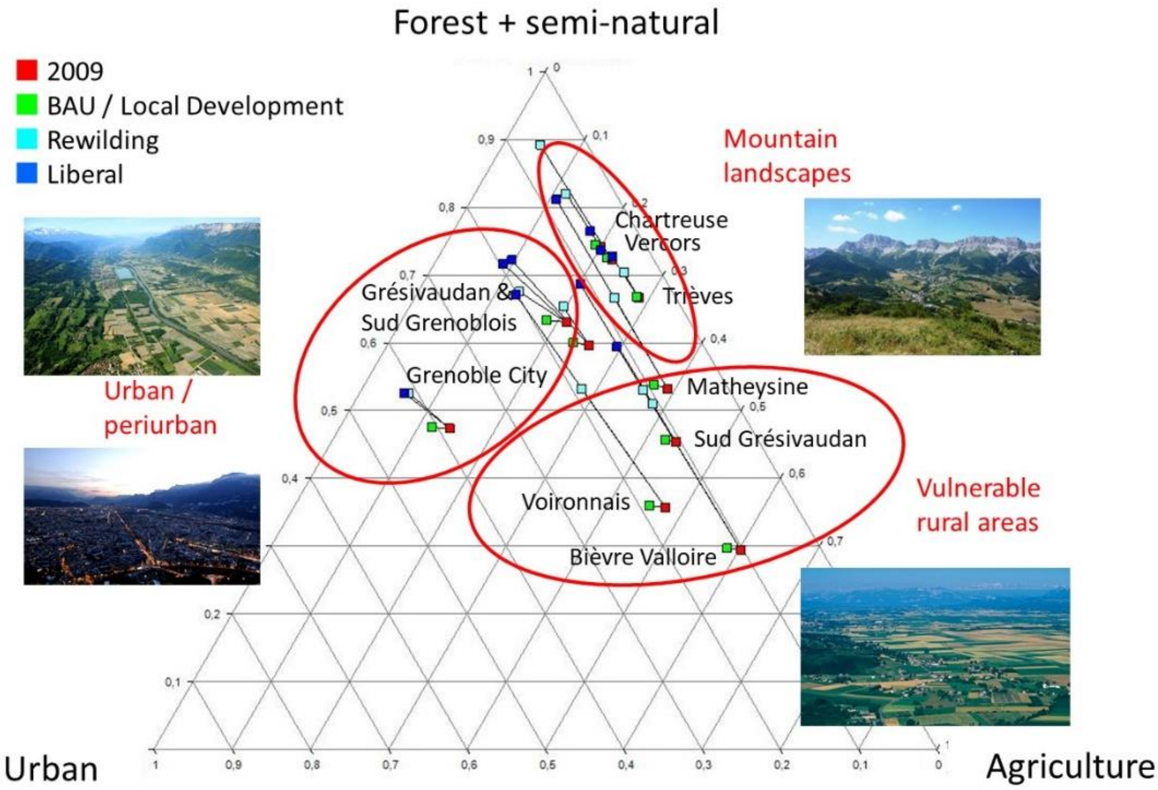


Figure 4 - Aggregated trajectories for districts of the Grenoble urban area. Each square positions percentage cover in the three-dimension space formed by (1) urban, (2) agriculture and (3) forest and semi-natural areas for initial state (2009) and the trend (BAU and Local development were not distinct at this scale), Rewilding and Liberal scenarios. Districts are clustered (red ellipses) according to their similar initial states and trajectories across scenarios.

## 3.4. Changes in spatial patterns

While model design prescribed consistent mechanisms across scenarios, with urbanisation occurring at the expense of agricultural land, as did woody encroachment and forest expansion, loss of agricultural land varied across scenarios, with more or less spatial continuity, as did the increase in built-up and forested areas. Landscape metrics provided a finer-scale analysis of these spatial changes within the scenarios. They were complemented by analyses of ecological connectivity for forest and semi-natural areas (Appendix A).

In spite of their slight differences e.g. in green corridor dynamics, the trend scenarios (BAU, LD) produced similar changes in overall landscape spatial pattern (Figure 5, and Supplementary table 6 for detailed results). Change rates were unabated from the initial 1998-2009 period with consolidation into fewer and larger new built-up patches contiguous to currently existing urban areas (Figure 5). Likewise changes in patch number and size of individual agricultural and forest land cover types were small and stable over time. Only the mean size of agricultural patches decreased slightly more in the projections as compared to 1998-2009 trends (while their number remained stable), reflecting consolidation of pre-existing built-up patches (Figure 5).

This contrasts with the two break-away scenarios, with overall much greater changes and trends not always consistent with those observed between 1998 and 2009 (Figure 5). The two scenarios were marked by increasing trends in total forested area. These changes of forested areas are mechanistically linked with those in agricultural land, with the two scenarios producing opposite changes in spatial patterns: under Rewilding agricultural abandonment adjacent to existing forest areas increased forest connectivity (see Supplementary analysis 1). In contrast under the Liberal scenario while abandonment occurred randomly, due to its magnitude the number and size of agricultural patches decreased, inducing a 30% reduction in the number of forest patches and a near doubling of forest mean patch size compared to 2009. The contrasting forest dynamics of the two scenarios were linked with changes in patterns of built-up land. Under Rewilding urbanisation followed the 1998-2009 trends, with similar changes in spatial patterns as for the trend scenarios (Figure 5). The Liberal scenario, however, was marked by an acceleration of peri-urbanisation into agricultural areas with more numerous and slightly smaller urban patches compared to 2009.

The land cover diversity increased slightly between 1998 and 2009, and continued to increase under the four scenarios (Figure 5 and Supplementary table 6, Shannon Diversity Index SHDI). While this rate of increase was stable for the two trend scenarios, it increased by half for the Rewilding scenario due to the predominance of continuous patches of a single LULC class (forest). Conversely it was halved for the Liberal scenario, reflecting a more even distribution of LULC classes in a more fragmented landscape (Figure 5).

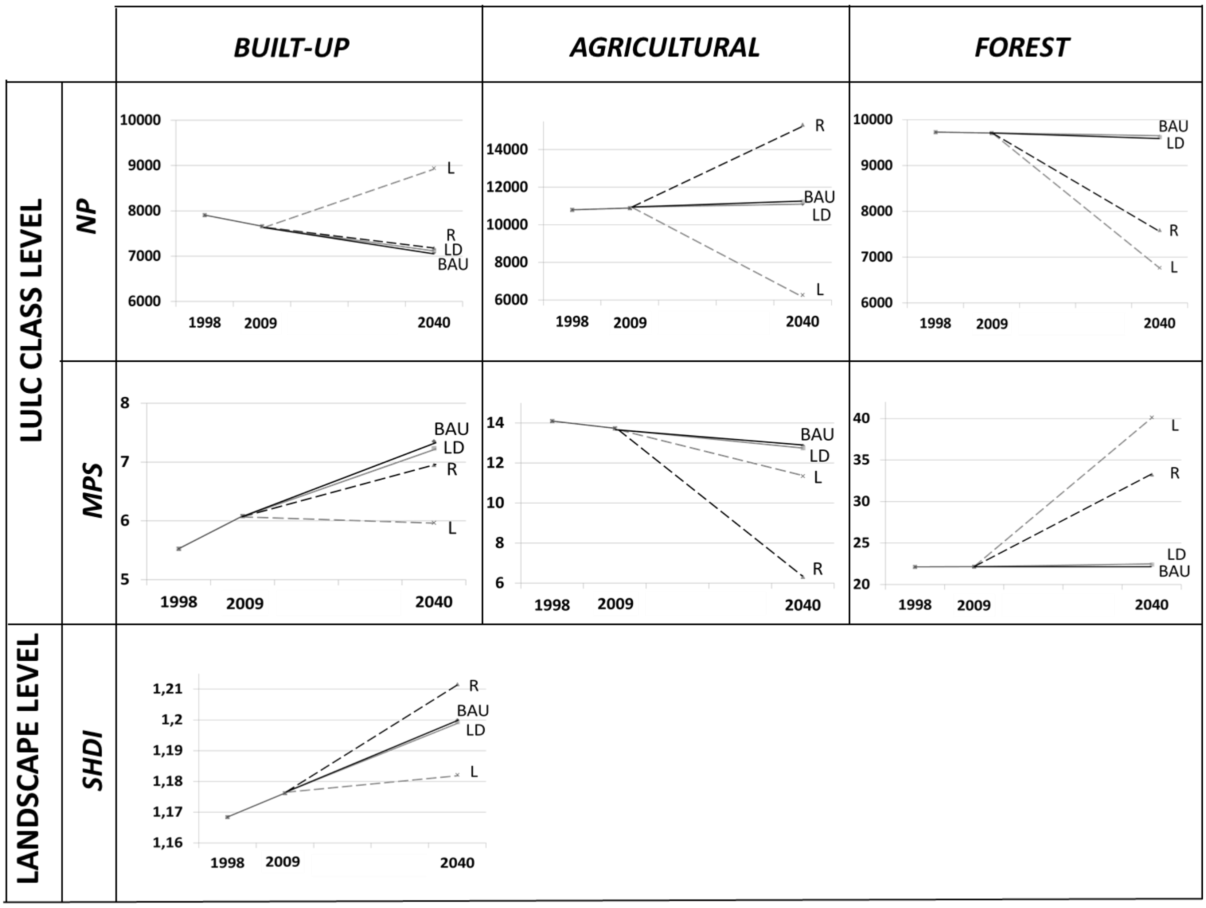

Figure 5 – Landscape metrics at the LULC class level (NP: number of patches, MPS: mean patch size) and at landscape level (SDHI: Shannon Diversity Index): columns present LULC metrics for the three main classes undergoing greatest changes. Scenarios: BAU: Business as usual, LD: Local development, R: Rewilding, L: Liberal.

# 4. Discussion

## 4.1. Benefits of participatory normative scenario downscaling

Multi-scale scenarios are considered as particularly relevant to support local or regional decisions by incorporating multiple decision scales, facilitating communication and appropriation by stakeholders and examining local ecological impacts (Biggs et al. 2007). Here we developed a highly participatory downscaling approach allowing a qualitative coupling between normative scenarios designed by policy makers at regional scale and local, spatially explicit dynamics contributed by stakeholders during the participatory process, and refined through quantitative spatial modelling. Four scenarios and accompanying storylines and land use projections translating socio-economic, climate and ecological constraints within normative visions were co-constructed between stakeholders representing main activities and an interdisciplinary research team. Our normative downscaling approach contrasts with common practice for participatory scenario planning (PSP) in place-based socio-ecological research, which has largely favoured exploratory scenarios combining socio-economic and climate drivers (Oteros-Rozas et al. 2015), usually based on bottom-up articulation of past trends and known drivers of land use change and ecosystem service demand (e.g. Hanspach et al. 2014; Mitchell et al. 2015; Schirpke et al. 2017). First, explicit downscaling approaches remain rare in PSP (Harmáčková and Vačkář 2018; Lamarque et al. 2013) probably due to costs and difficulties of such iterative, participatory processes (Walz et al. 2007). While in many PSP processes scenario generation is completed over a short period with a single workshop, here co-production spanned over nearly two years and involved two full time researchers and a team of collaborators contributing the equivalent of another year full time.

Second, the lesser adoption of normative scenarios in PSP may be surprising given their value for incorporating stakeholder visions about desirable futures and associated solutions, and for guiding policy and decision-making (Kok et al. 2017). With this study, we contribute to developing practice in normative scenario co-production (Rosa et al. 2017), using an original and replicable participatory downscaling approach combining qualitative and quantitative methods (Harmáčková and Vačkář 2018; Kok et al. 2017; Walz et al. 2007), and that meets criteria of relevance, credibility, legitimacy and creativity (Alcamo et al. 2005).

The Montagne 2040 policy initiative, depicting four visions for the Rhône-Alpes region's socio-cultural, economic and governance future was an asset for the project given their high relevance to local policy and planning. Similar to other national or regional initiatives (e.g. Pedroli et al. 2015, Grünenfelder et al. 2018), including some national scenarios analysed during our first step scoping (MEDDE 2015), these top-down visions were expressed as main components of socio-economic development for public communication and political action, but without quantification or spatial projections. Familiarity of stakeholders with these initial storylines both facilitated the engagement process for their local adaptation, but also raised normative views and issues of political and power relationships: local stakeholders felt that their innovative (Grenoble was one of the first SCoT plans developed and operationalised in France), and socially and environmentally proactive initiative for reconciling development and conservation of natural capital, was not recognised in Montagne 2040. Stakeholder involvement into adapting storylines insures that their expectations and local context are incorporated, thereby strengthening legitimacy (Castella et al. 2014). As a case in point, the Local Development scenario was developed to address this concern. Although at the time horizon considered here, projected land cover differences were minimal with the Business as usual scenario, researchers' effort for adding this scenario were essential for legitimacy. Stakeholders considered the more extreme scenarios from Montagne 2040 (Rewilding and Liberal) as push-backs, and never fully appropriated Rewilding (Brunet et al. 2018). Nevertheless researchers insisted on developing this scenario, which reflects a political debate in Europe (Pettorelli et al. 2018). Such a give and take attitude is critical for successful transdisciplinary research (Mauser et al. 2013).

Given the shared objective between researchers and stakeholders of incorporating ecosystem services into local planning from which the project originated, we needed to translate the directions articulated by Montagne 2040 storylines into land cover maps for subsequent ES modelling (Albert et al. 2014). Downscaling requires careful analysis by researchers of policy, regulation and external scenario documents to specify and quantify expected changes under each vision. Here, guidance from stakeholders was critical for identifying relevant documents and information, along with their specific inputs for missing parameters. Mountain regions require intensive efforts for incorporating their biophysical constraints and associated social contexts into detailed scenarios (Lamarque et al. 2013; Vacquie et al. 2015; Walz et al. 2007). Consistent with other PSP initiatives (Oteros-Rozas et al. 2015), the workshop provided a creative space where stakeholder provided in-depth, spatially-explicit knowledge and imaginative suggestions for the specification of scenarios for the eight sub-regional districts (Brunet et al. 2018). Furthermore, some strongly normative statements were made during this process, especially on power relationships and socio-cultural legacies likely to favour or limit innovation in different districts. This spatial specification was further enriched during the model parameterisation process by joint inputs from stakeholders and local scientific or technical experts. Ultimately, our iterative combination of local stakeholder expertise and planning document analyses, enabled district-specific parameterisation of state-of-the-art LULC models. Credibility and legitimacy of storylines and LULC projections were validated during a next-stage workshop in September 2015, where outputs were presented to the full stakeholder group as an introduction to the participatory analysis of future ecosystem service trade-offs. Main resulting modifications regarded naming and details of some of the more contested storylines, namely Local Development and Rewilding.

## 4.2. Projecting scenario land use impacts

Consistent with stakeholder expectations and the characteristics of the study area we chose to implement three nested LULC change models for urban, agricultural and forest areas. Each of these models and their scales of implementation were selected according to our analysis of recent dynamics (1998-2009; Vannier et al., 2016) and to data availability (Magliocca et al., 2015). LULC scenario modelling studies in mountains have instead used integrated spatial modelling platforms (FOREcasting SCEnarios - Sohl and Sayler, 2008 ; Land Change Modeler - Eastman, 2012 in the Pyrenees - Vacquie et al. (2015) and Houet et al. (2015); SPA-LUCC in the Austrian Alps - Schirpke et al. 2012), which are more generic and replicable. First rather than combining deterministic (agricultural and forest areas) and probabilistic (urban areas) methods as done here, they rely on common probabilistic models (Magliocca et al., 2015; Sohl and Sayler, 2008; Verburg et al., 2002), which they typically apply to simpler LULC typologies (7 classes on average) across smaller areas (from 7-35 km² - Schirpke et al., 2012, to 498 km² - Houet et al. 2015). Second, these models are parameterised and validated by multi-decadal LULC records (e.g. Tasser et al., 2007 in the Austrian Alps), but are not robust for modelling break-away scenarios.

An alternative, more complex and intensive approach was motivated by our multi-scenario objective, and by a search for the necessary spatial and typological precision across a highly diverse and heterogeneous region (Schirpke et al. 2017; Stürck and Verburg 2017). This however implied an enormous parameterisation effort for working at the agricultural parcel scale across an extent of 4450 km², with 41 land cover classes and specific parameters for eight heterogeneous districts. We nevertheless recommend such precision for LULC in heterogeneous, fine-grained landscapes, where processes of urban sprawl, changes in agricultural practices or land abandonment operate at very fine scales and, except for urban conversion, with gradual transitions rather than first-level LULC class conversions, which are relevant for ES modelling (Schirpke et al. 2012, Qiu and Turner 2013, Lasseur et al. 2018). We nevertheless acknowledge that even if pixel-level model allocations are necessarily uncertain as in any LULC model, projections enabled a precise description of changes in landscape patterns and practices at relevant scales for decision makers, namely municipality or district level. Our original LULC maps for the 1998-2009 period had a general mapping precision of at least 95% for level 3 typology (Vannier et al. 2016), and precision for crop successions was typically 35-88% (Lasseur et al. 2018). The spatial precision of the probabilistic model of urban dynamics was estimated to be greater than 10% at pixel level (Longaretti, unpublished data), and by construction the model was implemented so as to exactly reach change targets prescribed for each district. The appropriate scale for use of the maps and their uncertainties were clearly communicated and very well understood by stakeholders during subsequent steps of the work.

Projected scenario impacts were consistent with modelling studies for European mountain regions, showing polarisation of landscapes through urbanisation at the expense of agricultural land and forest colonisation of less productive areas (Schirpke et al., 2012; Houet et al. 2015 ; Vacquie et al., 2015; Stürck et al. 2016). However, the scenarios produced contrasting spatial patterns. While the two trend scenarios showed typical European patterns of spatially-continuous urban expansion into agricultural land (Stürck et al. 2016), the two break-away scenarios resulted in strong contrasts with 2009, and amongst themselves due to spatial contiguous vs. random land abandonment and reforestation. The reforestation of less productive land and the resulting landscape homogenisation under liberal economic settings is a common feature of scenarios for mountains (Schirpke et al., 2012; Vacquie et al., 2015; Brunner et al. 2017) and other cultural landscapes (Hanspach et al. 2014; Plieninger et al. 2013), and at European scale (Stürck et al. 2016). However the deliberately contiguous pattern proposed under Rewilding for developing ecological connectivity has rarely been considered in spite of this scenario's plausibility in the European policy context (Schulp et al. 2016; Stürck et al. 2016) and growing interest by the conservation community (Pettorelli et al. 2018). Landscapes metrics strongly benefit land planning in addition to analyses of change volumes (De Vreese et al., 2016), especially when applied to scenarios (Lausch et al., 2015). Given European and national green and blue corridors policy targets, it is essential to document alternatives in terms of landscape pattern and connectivity (De Vreese et al., 2016). Connectivity analysis also integrates relevant ecological characteristics (Rao et al., 2019). The value of such analyses was thus evident for distinguishing environmental benefits across the two break-away scenarios. On the other hand, while stakeholders insisted in distinguishing the Local development scenarios from Business as Usual based on governance and stronger urban consolidation constraints, spatial differences were not detectable. We expect that, given the relatively low rates of urban expansion, their differences in urban growth forms would become evident over longer time horizons. Lastly, connectivity in agricultural areas improved under all scenarios, complying with European and national legislation (French Law for Biodiversity and Landscapes 2016).

### 4.3. Implications for ecosystem services

The use of scenarios offers new perspectives for integrated planning that takes into account ecological dynamics and ecosystem services (Opdam et al. 2015). Significant implications of each scenario and associated LULC projections for future ecosystem service supply capacity are expected. Apart from obvious differences in provisioning services across scenarios due to their fundamentally different economies, projected changes in land cover would differently impact regulation services that strongly depend on forest cover such as carbon storage, water quality and quantity regulation or erosion and rockfall control. While increased wood stocks in the two break-away scenarios would increase carbon storage, their economic context would not necessarily promote wood production (Lafond et al. 2017). Their positive effects on regulation services would also trade-off with loss in crop and fodder provisioning (Harmáčková and Vačkář 2018; Schirpke et al. 2017; Stürck and Verburg 2017). Scenario contrasts in forest cover and spatial pattern, agricultural land and urban development would also affect cultural services as limited forest expansion is perceived positively (e.g. recreation, Byczek et al. 2018; aesthetic value – Schirpke et al. 2019) and favours some protected species. Spatial differences between scenarios will specifically impact regulation services dependent on lateral flows of matter and organisms (e.g. water quality and quantity regulation, erosion control, pollination; Verhagen et al. 2016) or cultural services depending on landscape connectivity (e.g. cultural value of protected vertebrates; Schirpke et al. 2018) or landscape heterogeneity (e.g. outdoor recreation; Byczek et al. 2018).

## 5. Concluding remarks: Implications for land use planning and decision

Through a structured and sustained two-year participatory process, our interdisciplinary research team co-produced with local stakeholders scenario narratives and associated land use projections downscaling four normative scenarios produced by the administrative region's government. This process relevant to similar urban regions in developed mountain and other regions fostered (i) local appropriation of top-down visions, (ii) incorporation of participants normative views, (iii) simultaneous consideration of local initiatives for reconciling economic development with the conservation of natural resources and processes, and of national and European policy challenges, and (iv) incorporation of biophysical and socio-economic heterogeneity and legacies. Final mapped scenarios described how landscape transformations that are common across mountain and other culturally valued regions would unfold in the Grenoble context. They highlighted how pairs of scenarios distinct in their baseline values and associated governance, namely the two trend scenarios (BAU and Local development) or the two break-away scenarios (Rewilding and Liberal), could converge to similar landscape outcomes – curbing periurban sprawl or extensive forest expansion respectively. Nevertheless, the stark contrast in landscape patterns for the two break-away scenarios strongly supported the use of a fine-scale, detailed spatially-explicit approach incorporating sub-regional specificities essential to stakeholders. As such projected LULC maps, along with their detailed context elements and parameters, can readily be used by land planners and nature managers. For instance, they are of direct relevance for the ongoing implementation of the French national ecological connectivity strategy, or for the management and development of natural protected areas – including a new regional park proposed for the Belledonne range. Forthcoming projections of scenario impacts on current bundles of ecosystem services (Vannier et al., 2019) will add to land planners and decision managers baseline knowledge and know how, and challenge their preconceptions of the costs and benefits of alternative development trajectories (Brunet et al. 2018).

## References

Albert C, Aronson J, Fürst C, Opdam P (2014) Integrating ecosystem services in landscape planning: requirements, approaches, and impacts. Landscape Ecology 29(8):1277-1285

Alcamo J (ed) (2009) Environmental Futures: The Practice of Environmental Scenario Analysis. Elsevier

Alcamo J, van Vuuren D, Ringler C et al (2005) Changes in nature's balance sheet: model-based estimates of future worldwide ecosystems. Ecology and Society 10(2):19

Bierry, A., Lavorel, S., 2016. Implication des parties prenantes d'un projet de territoire dans l'élaboration d'une recherche à visée opérationnelle. Sciences, Eaux & Territoires 21, http://www.set-revue.fr/sites/default/files/articles/pdf/set-revue-gestion-territoires-recherche-implication-acteurs.pdf.

Biggs R, Raudsepp-Hearne C, Atkinson-Palombo C et al (2007) Linking Futures across Scales: a Dialog on Multiscale Scenarios. Ecology and Society 12(1)

Bohunovsky L, Jäger J, Omann I (2011) Participatory scenario development for integrated sustainability assessment. Regional Environmental Change 11(2):271-284

Brunet L, Tuomisaari J, Lavorel S et al (2018) Actionable knowledge for land-use planning: making ecosystem services operational. Land Use and Policy 72:27-34

Brunner SH, Huber R, Grêt-Regamey A (2017) Mapping uncertainties in the future provision of ecosystem services in a mountain region in Switzerland. Regional Environmental Change

Byczek, C., Longaretti, P.-Y., Renaud, J., Lavorel, S. (2018) Benefits of crowd-sourced GPS information for modelling the recreation ecosystem service. PLOS ONE 13, e0202645. https://doi.org/10.1371/journal.pone.0202645

Cabral P, Feger C, Levrel H, Chambolle M, Basque D (2016) Assessing the impact of land-cover changes on ecosystem services: A first step toward integrative planning in Bordeaux, France. Ecosystem Services 22, part B:318-327

Carpenter SR, Mooney HA, Agard J et al (2009) Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. Proceedings of the National Academy of Sciences 106:1305-1312

Castella, J.-C., J. Bourgoin, G. Lestrelin and B. Bouahom (2014). "A model of the science–practice–policy interface in participatory land-use planning: lessons from Laos." Landscape Ecology 29(6): 1095-1107.

Centre Economique, Social et Environnemental Régional Rhône-Alpes (2013) Montagne 2040. 2013-03. Région Rhône-Alpes, pp. 228

Colloff MJ, Martín-López B, Lavorel S et al (2017) An integrative framework for enabling transformative adaptation. Environmental Science & Policy 68:87-96

Cradock-Henry, N.A., Frame, B., Preston, B.L., Reisinger, A., Rothman, D.S., 2018. Dynamic adaptive pathways in downscaled climate change scenarios. Climatic Change 150, 333-341.

Cushman, S.A., McGarigal, K., Neel, M.C., 2008. Parsimony in landscape metrics: Strength, universality, and consistency. Ecol. Indic. 8, 691–703. https://doi.org/10.1016/j.ecolind.2007.12.002

De Vreese, R., Leys, M., Fontaine, C.M., Dendoncker, N., 2016. Social mapping of perceived ecosystem services supply – The role of social landscape metrics and social hotspots for integrated ecosystem services assessment, landscape planning and management. Ecological Indicators 66, 517–533. https://doi.org/10.1016/j.ecolind.2016.01.048

Díaz S, Demissew S, Carabias J et al (2015) The IPBES Conceptual Framework — connecting nature and people. Current Opinion in Environmental Sustainability 14(0):1-16

Eastman, 2012. Idrisi Selva, Guide to GIS and Image Processing.

Griggs D, Stafford-Smith M, Gaffney O et al (2013) Sustainable development goals for people and planet. Nature 495:305

Grünenfelder, P., Schellenbauer, P., Dümmler, P., Langenegger, J., Parzer-Epp, V., Salvi, M., Schaad, J., Schnell, F., Steiner, U., 2018. Livre Blanc Suisse - Six esquisses pour l'avenir. Avenir Suisse, Zürich, p. 35.

Hanspach J, Hartel T, Milcu AI et al (2014) A holistic approach to studying social-ecological systems and its application to southern Transylvania. Ecology and Society 19(4)

Harmáčková ZV, Vačkář D (2018) Future uncertainty in scenarios of ecosystem services provision: Linking differences among narratives and outcomes. Ecosystem Services

Harrison PA, Dunford R, Savin C et al (2015) Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors. Climatic Change 128:279-294

Houet, T., Vacquié, L., Sheeren, D. (2015) Evaluating the spatial uncertainty of future land abandonment in a mountain valley (Vicdessos, Pyrenees - France): Insights from model parameterization and experiments. J. Mt. Sci. 12, 1095–1112. https://doi.org/10.1007/s11629-014-3404-7

Kabisch N, Frantzeskaki N, Pauleit S et al (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society 21(2)

Kohler M, Stotten R, Steinbacher M et al (2017) Participative Spatial Scenario Analysis for Alpine Ecosystems. Environmental Management 60(4):679-692

Kok K, Biggs R, Zurek M (2007) Methods for developing multiscale participatory scenarios: insights from southern Africa and Europe. Ecology and Society 13

Kok MTJ, Kok K, Peterson GD, Hill R, Agard J, Carpenter SR (2017) Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. Sustainability Science 12(1):177-181

Lafond, V., T. Cordonnier, Z. Mao and B. Courbaud (2017). "Trade-offs and synergies between ecosystem services in uneven-aged mountain forests: evidences using Pareto fronts." European Journal of Forest Research: 1-16.

Lamarque P, Artaux A, Nettier B, Dobremez L, Barnaud C, Lavorel S (2013) Taking into account farmers' decision making to map fine-scale land management adaptation to climate and socio-economic scenarios. Landscape and Urban Planning 119:147-157

Lasseur, R., Vannier, C., Lefebvre, J., Longaretti, P.-Y., Lavorel, S. (2018) Landscape-scale modeling of agricultural land use for the quantification of ecosystem services. J. Appl. Remote Sens. 12, 046024. https://doi.org/10.1117/1.JRS.12.046024

Lausch, A., Blaschke, T., Haase, D., Herzog, F., Syrbe, R.-U., Tischendorf, L., Walz, U., 2015. Understanding and quantifying landscape structure – A review on relevant process characteristics, data models and landscape metrics. Ecological Modelling, Use of ecological indicators in models 295, 31–41. https://doi.org/10.1016/j.ecolmodel.2014.08.018

Lavorel, S., Colloff, M.J., Locatelli, B., Gorddard, R., Prober, S.M., Gabillet, M., Devaux, C., Laforgue, D., Peyrache-Gadeau, V., 2019. Mustering the power of ecosystems for adaptation to climate change. Environ. Sci. Policy 92, 87–97. https://doi.org/10.1016/j.envsci.2018.11.010

Maes J, Sanders NJ (2017) Nature-based solutions for Europe's sustainable development. Conservation Letters 10:121-124

Magliocca, N.R., van Vliet, J., Brown, C., Evans, T.P., Houet, T., et al. (2015) From meta-studies to modeling: Using synthesis knowledge to build broadly applicable process-based land change models. Environ. Model. Softw. 72, 10–20. https://doi.org/10.1016/j.envsoft.2015.06.009

Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B.S., Hackmann, H., Leemans, R., Moore, H., 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability. Current Opinion in Environmental Sustainability 5, 420-431.

McGarigal, K., Cushman, S., Ene, E. (2012) Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at the following web site: http://www.umass.edu/landeco/research/fragstats/fragstats.html.

Ministere de l'Ecologie, du Developpement Durable et de l'Energie, 2015, Territoire Durable 2030, commissariat general au developpement durable, mission prospective. http://www.territoire-durable-2030.developpement-durable.gouv.fr/

Mitchell MGE, Bennett EM, Gonzalez A et al (2015) The Montérégie Connection: linking landscapes, biodiversity, and ecosystem services to improve decision making. Ecology and Society 20(4)

Moss RH, Edmonds JA, Hibbard KA et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747-756

Nesshöver C, Assmuth T, Irvine KN et al (2017) The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Science of The Total Environment 579:1215-1227

Nieto-Romero M, Milcu A, Leventon J, Mikulcak F, Fischer J (2016) The role of scenarios in fostering collective action for sustainable development: Lessons from central Romania. Land Use Policy 50:156-168

Opdam P, Coninx I, Dewulf A, Steingröver E, Vos C, van der Wal M (2015) Framing ecosystem services: Affecting behaviour of actors in collaborative landscape planning? Land Use Policy 46(0):223-231

Oteros-Rozas E, Martín-López B, Daw T et al (2015) Participatory scenario-planning in place-based social-ecological research: insights and experiences from 23 case studies. Ecology & Society 20(4):32

Oteros-Rozas E, Martín-López B, López CA, Palomo I, González JA (2013) Envisioning the future of transhumant pastoralism through participatory scenario planning: a case study in Spain. The Rangeland Journal 35(3):251-272

Palomo I, Martin-Lopez B, Lopez-Santiago C, Montes C (2011) Participatory Scenario Planning for Protected Areas Management under the Ecosystem Services Framework: the Donana Social-Ecological System in Southwestern Spain. Ecology and Society 16(1)

Pedroli, B., Rounsevell, M. D. A., Metzger, M. J., Paterson, J., & The VOLANTE Consortium. (2015). *The VOLANTE Roadmap towards sustainable land resource management in Europe. VOLANTE final project document*. Wageningen: Alterra Wageningen UR.

Peterson GD, Cumming GS, Carpenter SR (2003) Scenario Planning: a Tool for Conservation in an Uncertain World

Pettorelli, N., Barlow, J., Stephens, P.A., Durant, S.M., Connor, B., Schulte to Bühne, H., Sandom, C.J., Wentworth, J., Toit, J.T., 2018. Making rewilding fit for policy. Journal of Applied Ecology 55, 1114-1125.

Plieninger T, Bieling C, Ohnesorge B, Schaich H, Schleyer C, Wolff F (2013) Exploring Futures of Ecosystem Services in Cultural Landscapes through Participatory Scenario Development in the Swabian Alb, Germany. Ecology and Society 18(3)

Plieninger T, van der Horst D, Schleyer C, Bieling C (2014) Sustaining ecosystem services in cultural landscapes. Ecology and Society 19(2)

Qiu, J., Turner, M.G., 2013. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proceedings of the National Academy of Sciences 110, 12149-12154.

Rao, Y., Zhang, J., Wang, K., Wu, X., 2019. How to prioritize protected areas: A novel perspective using multidimensional land use characteristics. Land Use Policy 83, 1–12. https://doi.org/10.1016/j.landusepol.2019.01.023

Reed MS, Hubacek K, Bonn A et al (2013) Anticipating and Managing Future Trade-offs and Complementarities between Ecosystem Services. Ecology and Society 18(1)

Rosa IMD, Pereira HM, Ferrier S et al (2017) Multiscale scenarios for nature futures. Nature Ecology & Evolution 1(10):1416-1419

Rounsevell MDA, Pedroli B, Erb K-H et al (2012) Challenges for Land System Science. Land Use and Policy 29:899-910

Ruget F., Bernard F., Durand J.L., Graux A.I., Lacroix B., Moreau J.-C., Ripoche D., 2013, « Impacts des changements climatiques sur les productions de fourrages (prairies, luzerne, maïs) : variabilité selon les régions et les saisons », *Fourrages*,*214*, p. 99-110.

Schirpke U, Kohler M, Leitinger G, Fontana V, Tasser E, Tappeiner U (2017) Future impacts of changing land-use and climate on ecosystem services and resilience of mountain grassland. Ecosystem Services 26:79-94

Schirpke, U., Leitinger, G., Tappeiner, U., Tasser, E., 2012. SPA-LUCC: Developing land-use/cover scenarios in mountain landscapes. Ecol. Inform. 12, 68–76. https://doi.org/10.1016/j.ecoinf.2012.09.002

Schirpke, U., Meisch, C., Tappeiner, U., 2018. Symbolic species as a cultural ecosystem service in the European Alps: insights and open issues. Landscape Ecology 33, 711-730.

Schirpke, U., G. Tappeiner, E. Tasser and U. Tappeiner (2019). "Using conjoint analysis to gain deeper insights into aesthetic landscape preferences." Ecological Indicators 96: 202-212.

Schulp CJE, Van Teeffelen AJA, Tucker G, Verburg PH (2016) A quantitative assessment of policy options for no net loss of biodiversity and ecosystem services in the European Union. Land Use Policy 57:151-163

Seidl, R., Schelhaas, M.-J., Lexer, M.J., 2011. Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob. Change Biol. 17, 2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x

Sharpe, B., Hodgson, A., Leicester, G., Lyon, A., Fazey, I., 2016. Three horizons: a pathways practice for transformation. Ecol. Soc. 21. https://doi.org/10.5751/ES-08388-210247

Steffen W, Richardson K, Rockström J et al (2015) Planetary boundaries: Guiding human development on a changing planet. Science 347(6223)

Soares-Filho, B., Rogrigues H., Follador, M. (2013) A hybrid analytical-heuristic method for calibrating land use change models, Environmental Modelling and Software, 43, 80-87. https://doi.org/10.1016/j.envsoft.2013.01.010

Sohl, T., Sayler, K. (2008) Using the FORE-SCE model to project land-cover change in the southeastern United States. Ecol. Model. 219, 17. https://doi.org/10.1016/j.ecolmodel.2008.08.003

Stürck J, Levers C, van der Zanden EH et al (2016) Simulating and delineating future land change trajectories across Europe. Regional Environmental Change in press

Stürck J, Verburg PH (2017) Multifunctionality at what scale? A landscape multifunctionality assessment for the European Union under conditions of land use change. Landscape Ecology 32:481-500

Tasser E, Walde J, Tappeiner U, Teutsch A, Noggler W (2007) Land-use changes and natural reforestation in the Eastern Central Alps. Agriculture, Ecosystems & Environment 118(1-4):115-129

Turkelboom F, Leone M, Jacobs S et al (2017) When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosystem Services:in press

Vacquie L, Houet T, Sohl T, Reker R, Sayler K (2015) Modelling regional land change scenarios to assess land abandonment and reforestation dynamics in the Pyrenees (France). J. Mt. Sci. 12(4):905-920

Van Kerkhoff, L., Munera, C., Dudley, N., Guevara, O., Wyborn, C., Figueroa, C., Dunlop, M., Hoyos, M.A., Castiblanco, J., Becerra, L., 2018. Towards future-oriented conservation: Managing protected areas in an era of climate change. Ambio.

Vannier C., Lasseur R., Crouzat E., Byczek C., Lafond V., Cordonnier T., Longaretti P.Y., Lavorel S. (2019) Mapping Ecosystem Services bundles in a heterogeneous mountain region, Ecosystems and People, 15(1), 74-88. https://doi.org/10.1080/26395916.2019.1570971

Vannier, C., Lefebvre, J., Longaretti, P.-Y., Lavorel, S. (2016) Patterns of landscape change in a rapidly urbanizing mountain region. Cybergeo Eur. J. Geogr. https://doi.org/10.4000/cybergeo.27800

Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S.A., 2002. Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. Environ. Manage. 30, 391–405. https://doi.org/10.1007/s00267-002-2630-x

Verhagen, W., Van Teeffelen, A.J.A., Baggio Compagnucci, A., Poggio, L., Gimona, A., Verburg, P.H., 2016. Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. Landscape Ecology 41, 1457-1479.

Verkerk, P.J., Lindner, M., Pérez-Soba, M., Paterson, J.S., Helming, J., Verburg, P.H., Kuemmerle, T., Lotze-Campen, H., Moiseyev, A., Müller, D., Popp, A., Schulp, C.J.E., Stürck, J., Tabeau, A., Wolfslehner, B., van der Zanden, E.H., 2018. Identifying pathways to visions of future land use in Europe. Regional Environmental Change 18, 817-830.

Walz A, Lardelli C, Behrendt H et al (2007) Participatory scenario analysis for integrated regional modelling. Landscape and Urban Planning 81(1):114-131